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ANALYSIS OF THE DYNAMIC-LATERAL-STABILITY CHARACTERISTICS OF THE BELL X-2 AIRPLANE AS AFFECTED BY VARIATIONS IN MASS, AERODYNAMIC, AND DIMENSIONAL PARAMETERS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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RESEARCH MEMORANDUM

ANALYSIS OF THE DYNAMIC-LATERAL-STABILITY CHARACTERISTICS OF THE BELL X-2 AIRPLANE AS AFFECTED BY VARIATIONS IN MASS, AERODYNAMIC, AND DIMENSIONAL PARAMETERS

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SUMMARY

An analysis of the dynamic-lateral-stability characteristics of the Bell X-2 airplane as affected by variations in mass, aerodynamic, and dimensional parameters has been made by means of calculations of the period and rate of damping of the lateral oscillation. The analysis was made for a landing configuration (flaps and gear down) and a high-speed configuration (flaps and gear retracted) and included speeds up to a Mach number of 0.87.

The dynamic lateral stability of the airplane in the landing configuration was found to depend rather critically on the damping in roll, the damping in yaw, the inclination of the principal axis, and the radius of gyration about the principal longitudinal axis. In the high-speed configuration the dynamic lateral stability depended critically on the inclination of the principal axis. The calculations indicated dynamic lateral stability of the airplane for the high-speed configuration throughout the lift-coefficient range investigated, but indicated stability only at lift coefficients greater than about 0.75 for the landing configuration. The airplane met the USAF requirements for satisfactory period-damping relationship of the lateral oscillation throughout the range of lift coefficients investigated for the high-speed configuration, but met the requirements only at lift coefficients near 1.0 in the landing configuration.

Some improvement of the dynamic-lateral-stability characteristics of the airplane in the landing configuration seemed possible by decreasing the wing incidence, decreasing the geometric dihedral, or increasing the vertical-tail size. Of these three, only an increase in tail size had any appreciable stabilizing effect. However, increasing the tail size also caused the stability to be slightly

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less satisfactory in the high-speed configuration relative to the USAF criterion for satisfactory period-damping relationship of the lateral oscillation.

INTRODUCTION

The problem of estimating the dynamic-lateral-stability characteristics of high-speed aircraft is extremely complex because of the large number of important mass and aerodynamic parameters involved and the great range through which some of the parameters may vary (references 1 and 2). As a result of the complexity of the problem, it has been found impractical, at least up to the present time, to attempt to make general charts or tables from which the dynamic-lateral-stability characteristics of any airplane might be estimated. Therefore, it has been found expedient to calculate the lateral-stability characteristics of specific high-speed-airplane configurations.

Many of the mass and aerodynamic parameters required for such investigations generally are not known to a high degree of accuracy; therefore, the quantitative results may be questionable with regard to the actual airplane under consideration. Arbitrary variations of the parameters, however, should give a reasonably reliable indication of the effects of possible modifications to the airplane or of changes in the flight attitude.

The present investigation is concerned with the Bell X-2 high-speed research airplane (fig. 1). A similar investigation has been reported for the Douglas D-558-2 airplane (reference 3).

SYMBOLS AND COEFFICIENTS

The symbols and coefficients used herein are defined as follows:

h altitude, feet

α angle of attack of airplane reference axis (fig. 2), degrees

β	angle of sideslip, radians
γ	angle of flight path to horizontal axis, positive in climb (fig. 2), degrees
δ_s	split-flap deflection, degrees
δ_n	nose-flap deflection, degrees
ρ	mass density of air, slugs per cubic foot
b	wing span, feet
S	wing area, square feet
A	aspect ratio $\left(b^2/S\right)$
l	distance from airplane center of gravity to center of pressure of vertical tail, feet
z	perpendicular distance from fuselage center line to center of pressure of vertical tail, feet
W	weight of airplane, pounds
m	mass of airplane, slugs
η	inclination of principal longitudinal axis of airplane with respect to flight path, positive when principal axis is above flight path at the nose (fig. 2), degrees
ϵ	angle between fuselage reference axis and principal longitudinal axis, positive when reference axis is above principal axis at nose (fig. 2), degrees
k_{x_o}	radius of gyration about principal longitudinal axis, feet
$k_{\cancel{x}_o}$ z	radius of gyration about principal normal axis, feet
q	dynamic pressure, pounds per square foot $\left(\rho V^2/2\right)$

C_L trim lift coefficient $(W \cos \gamma / qS)$

C_Y lateral-force coefficient (Lateral force/qS)

C_l rolling-moment coefficient (Rolling moment/qSb)

C_n yawing-moment coefficient (Yawing moment/qSb)

V airplane velocity, feet per second

p rolling angular velocity, radians per second

r yawing angular velocity, radians per second

M Mach number (V/Local speed of sound)

$T_{1/2}$ time required for lateral oscillation to reduce to half amplitude, seconds

T_2 time required for lateral oscillation to double amplitude, seconds

$C_{1/2}$ cycles required for lateral oscillation to reduce to half amplitude

C_2 cycles required for lateral oscillation to double amplitude

P period of lateral oscillation, seconds

$$C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$$

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$$

$$C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$$

$$C_{Y_p} = \frac{\partial C_Y}{\partial \frac{pb}{2V}}$$

$$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}}$$

$$C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}}$$

$$C_{Y_r} = \frac{\partial C_Y}{\partial \frac{rb}{2V}}$$

$$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$$

$$C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$$

SCOPE AND METHOD

This investigation included the calculation of the dynamic lateral-stability characteristics of the Bell X-2 airplane in the high-speed configuration (flaps and gear retracted) at sea level and at an altitude of 35,000 feet, and in the landing and take-off configurations (flaps and gear lowered). The effects on the lateral stability of varying the parameters C_{n_p}, C_{l_p}, C_{n_r}, k_{X_0}, k_{Z_0}, and η also were investigated for a high-speed configuration and for a landing configuration. In determining the effects of these parameters, C_{n_p}, C_{l_p}, and C_{n_r} were varied ±50 percent; k_{X_0} and k_{Z_0} were varied ±20 percent; and η was varied ±2°. These variations are believed to cover the maximum probable error in estimating the parameters involved. In determining the effects of these parameters, one parameter was varied at a time. Possible variations in the static-lateral-stability parameters have not been considered since wind-tunnel determinations of these quantities were available.

All calculations were made for level-flight conditions and were made with the use of the equations of reference 2. Power effects were neglected as they were believed to be small. The highest Mach number for which calculations were made was about 0.87. Compressibility effects were neglected in most of the calculations. In order to evaluate these effects, however, additional calculations were made for one airplane configuration in which all the wing and vertical-tail derivatives were corrected for compressibility effects. The corrections were applied as indicated in reference 4.

Comparisons of calculated and measured periods and rates of damping for other airplanes have indicated that calculations generally predict period and rate of damping quite well if the lateral oscillation is of large amplitude, but show poor agreement when the oscillation is of very small amplitude. It is believed that small-amplitude oscillations might be caused by separation effects; hence if such effects occur on the airplane under consideration, the resulting rate of damping probably will be in poor agreement with the calculated rate of damping.

MASS AND AERODYNAMIC PARAMETERS

The mass and aerodynamic parameters used in this investigation are presented in table I. The static-stability parameters C_{l_β} and C_{n_β} for the complete airplane, and the parameters C_{Y_β}, C_{l_β} and C_{n_β} for the airplane with the vertical tail off were obtained from reference 5. The rotary derivatives C_{Y_p}, C_{l_p}, C_{n_p}, C_{Y_r}, C_{l_r}, and C_{n_r} for the airplane without the vertical tail were estimated with the aid of references 6, 7, and 8. The vertical-tail contributions to the rotary derivatives were estimated by the use of equations similar to those of reference 9.

All mass parameters used in this investigation were obtained from reference 10.

RESULTS AND DISCUSSION

Presentation of Results

The results of this investigation are presented in two groups, one for the airplane with flaps and landing gear retracted (high-speed configuration) and the other for the airplane with flaps and landing gear extended (landing or take-off configuration).

In the first group (high-speed configuration) are shown:

(a) The variation of period and rate of damping of the lateral oscillation with lift coefficient for a wing loading of 79.4 pounds per square foot and for altitudes of 35,000 feet, and sea level (fig. 3)

(b) Comparison of the period and damping characteristics of the lateral oscillation with the USAF criterion for satisfactory period-damping relationship (fig. 4)

(c) Effect on the period and damping of the lateral oscillation of varying the parameters C_{l_p}, C_{n_p}, C_{n_r}, k_{X_0}, k_{Z_0}, and η (fig. 5)

(d) Calculated effects of compressibility on the period and damping characteristics of the lateral oscillation (figs. 6 and 7)

In the second group of figures (for the landing or take-off configuration, sea-level flight) are shown:

(a) The variation of the period and damping of the lateral oscillation with lift coefficient for wing loadings of 33.3 and 79.4 pounds per square foot (fig. 8)

(b) Comparison of the calculated period and damping characteristics of the lateral oscillation with the USAF criterion for satisfactory period-damping relationship for wing loadings of 33.3 and 79.4 pounds per square foot (fig. 9)

(c) Effect on the period and damping of the lateral oscillation of varying the parameters C_{l_p}, C_{n_p}, C_{n_r}, k_{X_0}, k_{Z_0}, and η (fig. 10)

The rate of damping of the spiral and rolling modes of motion was calculated; however, the results are not presented in any of the figures. The pertinent results obtained for the lateral oscillation and the spiral and rolling modes are presented in table II.

In addition to the above, calculations were made to determine the effects of several assumed dimensional modifications to the airplane. The computed period and damping characteristics of the airplane with assumed changes in wing incidence, geometric dihedral, and tail area are shown in figure 11 for the landing configuration. The effect of increase in vertical-tail size on the period and damping characteristics for the airplane in the landing, take-off, and high-speed configurations is shown in figure 12.

Airplane with Flaps and Gear Retracted

Sea-level flight.– The calculated period and rate of damping of the lateral oscillation of the X-2 airplane flying at sea level with a wing loading of 79.4 pounds per square foot (corresponding to the airplane with almost a full fuel load) are shown by the solid lines of figure 3 as functions of the lift coefficient. It is seen that the lateral oscillation is heavily damped, requiring less than one cycle to damp to half amplitude. The present USAF criterion for satisfactory damping of the lateral oscillation is that the time required to damp to half amplitude must be less than 1.5 seconds if the period is between 0 and 2 seconds, and for periods greater than 2 seconds the oscillation must damp to half amplitude in less than 2.5P minus 3.5 seconds (reference 11). A graphical representation of this criterion is shown in figure 4. Also shown in figure 4 are several symbols representing the calculated period and damping of the lateral oscillation of the X-2 airplane at various lift coefficients. It can be seen that for sea-level flight the airplane meets the USAF criterion throughout the lift-coefficient range investigated.

According to the USAF criterion for the spiral mode, spiral stability is not required, but the allowable rate of divergence of the spiral mode must not be so great that the spiral motion will double amplitude in less than 4 seconds. It can be seen from table II that the airplane meets this requirement.

Effects of altitude.– The calculated period and damping of the lateral oscillation of the airplane flying at 35,000 feet altitude with a wing loading of 79.4 pounds per square foot are shown in figure 3 as functions of the lift coefficient. The lateral oscillation is heavily damped for the range of lift coefficients investigated and meets the USAF requirement for lift coefficients greater than about 0.35 (fig. 4). The spiral mode also meets the USAF requirement (table II). An increase in altitude caused a decrease in damping of the lateral oscillation (fig. 3); however, the decrease does not appear to be important for this particular configuration.

Effects of variations of aerodynamic and mass parameters.– The calculated effects on the period and damping of the lateral oscillation obtained by varying the parameters C_{l_p}, C_{n_p}, C_{n_r}, k_{X_0}, k_{Z_0}, and η are shown in figure 5. The calculations were made for the airplane flying at an altitude of 35,000 feet at a lift coefficient of 0.316 (M = 0.85) and a wing loading of 79.4 pounds per square foot. Also shown on the same figure are the changes in the oscillatory stability relative to the USAF criterion. The results indicate that only the variation of k_{Z_0} had any appreciable effect on the period and that the rate of damping (as indicated by $T_{1/2}$) was increased by making C_{n_p} or η more positive, by making C_{n_r} more negative, by making k_{X_0} smaller, or by making k_{Z_0} smaller. Making C_{l_p} more negative had little effect on $T_{1/2}$, but making it less negative decreased the rate of damping.

In each instance (except for the case of k_{Z_0}) for which variation of a parameter caused a reduction in $T_{1/2}$, the airplane oscillatory stability improved with reference to the USAF criterion. The reduction in $T_{1/2}$, resulting from a decreased value of k_{Z_0}, was accompanied by a relatively large reduction in period, so that the airplane oscillatory stability changed in an unfavorable manner according to the USAF criterion.

It should be noted that during these calculations each parameter was varied separately. The effects to be expected from the simultaneous variation of two or more parameters generally are not equal to the sum of the individual effects.

Effect of applying compressibility corrections to the aerodynamic derivatives.– None of the aerodynamic derivatives used in the calculations which have been discussed thus far were corrected for compressibility effects. In order to evaluate these effects, one set of calculations was made in which the period and rate of damping were calculated, with the wing and vertical-tail contributions to the stability derivatives corrected for the effects of compressibility as indicated in reference 4. The effects of applying compressibility corrections are shown in figure 6. The airplane was assumed to be flying at an altitude of 35,000 feet with a wing loading of 79.4 pounds per square foot. It is seen that the application of compressibility corrections resulted in a decrease in the period and a decrease in the rate of damping of the lateral oscillation. The curves of figure 7 show that when compressibility corrections are applied, satisfactory oscillatory stability characteristics, with reference to the USAF criterion, are indicated at lift coefficients greater than about 0.45. The neglect of compressibility corrections, therefore, results in optimistic estimates of the airplane characteristics, but does not seem particularly important for this airplane.

Airplane with Flaps and Gear Lowered

Sea-level flight.- The calculated period and damping characteristics of the lateral oscillation of the X-2 airplane flying at sea level with a wing loading of 33.3 pounds per square foot (corresponding to the airplane with most of its fuel exhausted) are shown by the solid curves of figure 8. The results of the calculations indicate that the airplane has oscillatory stability only at lift coefficients greater than about 0.75; however, even then the oscillation is poorly damped, so that the airplane meets the USAF criterion for satisfactory period-damping relationship only at lift coefficients near 1.0 (fig. 9).

Effects of wing loading.- The effects on the period and rate of damping of the lateral oscillation of increasing the wing loading from 33.3 pounds per square foot to 79.4 pounds per square foot are shown in figures 8 and 9 for sea-level flight with flaps and gear lowered. The results generally show a decrease in period and an increase in the rate of damping, at lift coefficients greater than about 0.6, as the wing loading is increased. It should be noted that the radii of gyration k_{X_0} and k_{Z_0} were decreased when the wing loading was increased (see table I), hence the changes in P and $T_{1/2}$ might well have been caused primarily by these changes rather than wing loading. This is substantiated to some extent by noting that the sum of the changes in P or $T_{1/2}$ caused by changing k_{X_0} and k_{Z_0} by the amounts shown in table I is about the same as the changes in P and $T_{1/2}$ shown in figure 8 (at $C_L = 1.0$).

The airplane appears to be satisfactorily stable at lift coefficients greater than about 0.8 with a wing loading of 79.4 pounds per square foot.

<u>Effects of variations in aerodynamic and mass parameters.</u>— The calculated changes in the period and rate of damping obtained by variation of the parameters C_{l_p}, C_{n_p}, C_{n_r}, k_{X_0}, k_{Z_0}, and η are shown in figure 10 for the airplane flying at sea level at a lift coefficient of 1.0 and a wing loading of 33.3 pounds per square foot. The assumed variations in the derivatives caused only small changes in the period of the lateral oscillation, but generally caused appreciable changes in the rate of damping. The time required for the lateral oscillation to reduce to half amplitude was decreased by making C_{l_p} or C_{n_r} more negative, by making C_{n_p} or η more positive, or by making k_{X_0} or k_{Z_0} smaller. In each instance (except possibly variations of k_{Z_0}) for which the variation of a parameter caused a reduction in $T_{1/2}$, the airplane oscillatory stability was improved with reference to the USAF criterion. The reduction in $T_{1/2}$, resulting from a decreased value of k_{Z_0}, was accompanied by a decrease in period, so that the airplane oscillatory characteristics showed no appreciable change relative to the USAF criterion.

Effects of Assumed Modifications to Airplane

The results of this investigation have indicated that the X-2 airplane has undesirable dynamic-lateral-stability characteristics with flaps and gear extended, and that, at high lift coefficients, the stability decreases as the wing loading is decreased (figs. 8 and 9). The calculations which were made by varying certain parameters (fig. 10) indicated that the oscillatory stability might be improved, at least at a lift coefficient of 1.0, by making C_{l_p} more negative, by making η more positive, by making C_{n_r} more negative, or by making k_{X_0} smaller. It is also known that dynamic lateral stability generally can be improved by increasing the vertical-tail size and a reduction in geometric dihedral. Thus it appears that such changes as decreasing the wing incidence (effectively increasing η), increasing the vertical-tail area (effectively increasing C_{n_r} negatively and C_{n_β} positively), or varying the geometric dihedral angle might improve the dynamic lateral stability. Calculations were made for the following assumed modifications:

(a) Decrease of wing incidence by 2°

(b) Decrease in geometric dihedral from 3° to 0°

(c) Increase in vertical-tail area (tail height increased until the tip chord was zero)

In making these calculations, one modification was assumed at a time. The results are shown in figure 11. It can be seen that decreasing the dihedral angle or the wing incidence caused no appreciable change in the period of the lateral oscillation, but did increase the rate of damping. These changes caused only a small improvement in the oscillatory stability relative to the USAF criterion. Increasing the vertical-tail area, however, caused a marked increase in the rate of damping of the lateral oscillation, especially at lift coefficients less than about 0.8; however, the period also was decreased. The net result was that although the added tail area improved the airplane stability it still was not satisfactory (relative to the USAF criterion) at lift coefficients less than about 0.7. It appears, however, that an increase in vertical-tail size would be beneficial to the lateral dynamic stability of the airplane in the landing configuration.

It should be noted that the effect of the increased vertical-tail size on the tail contributions to the various aerodynamic derivatives was based on the calculated value of the lift-curve slope of the vertical tail. The lift-curve slope was obtained from theoretical values based on the aspect ratio and sweep of the tail. Several experimental investigations have indicated that the theory used predicts values of the lift-curve slope which are too high, hence the improvement to be expected from the assumed tail modification probably would be less than indicated in figure 11. However, the figure does indicate proper trends.

Since the increase in vertical-tail area was beneficial for the landing configuration, calculations were made to determine the effects of the added tail area on the high-speed configuration and on the take-off configuration. The results indicated that an increase in vertical-tail area would cause a slight decrease in the dynamic lateral stability of the airplane with a wing loading of 79.4 pounds per square foot at an altitude of 35,000 feet and would cause a small improvement in the stability for lift coefficients greater than about 0.7 for the take-off configuration (flaps and gear down, wing loading of 79.4 pounds per square foot), judging only by the USAF criterion. The period and damping characteristics for a landing, take-off, and high-speed condition for the airplane with the added vertical-tail area are compared with the present USAF criterion for satisfactory period-damping relationship in figure 12.

Although the airplane with the assumed added tail area does not meet the USAF criterion at all lift coefficients for any of the assumed conditions (landing, take-off, high-speed flight), definitely undesirable characteristics are indicated only for the take-off or high wing-loading condition – and then only at lift coefficients smaller than about 0.6.

CONCLUSIONS

Calculations have been made to determine the effects of various mass, aerodynamic, and dimensional parameters on the dynamic-lateral-stability characteristics of the Bell X-2 airplane at Mach numbers up to 0.87. The results of the calculations have led to the following conclusions:

1. The dynamic lateral stability of the airplane in the landing configuration was found to depend rather critically on the damping in roll, the damping in yaw, the inclination of the principal axis, and the radius of gyration about the principal longitudinal axis. The dynamic lateral stability for the airplane in the high-speed configuration was found to depend rather critically on the inclination of the principal axis. Consideration of the effects of compressibility for speeds up to a Mach number of 0.87 was found to be relatively unimportant for this airplane.

2. The calculations indicated dynamic lateral stability of the airplane for the high-speed configuration (flaps and gear up) throughout the lift-coefficient range investigated, but indicated dynamic lateral stability only at lift coefficients greater than about 0.75 for the landing configuration.

3. The airplane met the USAF requirements for satisfactory period-damping relationship of the lateral oscillation throughout the range of lift coefficients investigated for the high-speed configuration, but

met the requirements only at lift coefficients near 1.0 in the landing configuration.

4. The calculations indicated dynamic lateral instability of the airplane in the landing configuration over a range of lift coefficients from 0.4 to 0.75. Some improvement seemed possible by decreasing the wing incidence, decreasing the geometric dihedral, or increasing the vertical-tail size. Of these three, only an increase in tail size had any appreciable stabilizing effect. However, an increase in tail area had a small unfavorable effect in the high-speed configuration, relative to the USAF criterion for satisfactory characteristics of the lateral oscillation.

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TABLE I.— ASSUMED BASIC STABILITY DERIVATIVES AND MASS CHARACTERISTICS OF THE X-2 AIRPLANE

Condition	Flaps and gear up (compressibility effects neglected)					Flaps and gear up (compressibility effects included)				Flaps and gear down (compressibility effects neglected)				Flaps and gear up (modified vertical tail, compressibility effects neglected)				Flaps and gear down (modified vertical tail, compressibility effects neglected)			
C_L	0.3	0.316	0.4	0.6	0.8	0.3	0.4	0.6	0.8	0.4	0.6	0.8	1.0	0.3	0.4	0.6	0.8	0.4	0.6	0.8	1.0
α, deg	2.45	2.8	4.1	7.2	13.5	1.9	3.1	6.3	12.5	-1.7	1.6	5.2	9.0	2.45	4.1	7.2	13.5	-1.7	1.6	5.2	9.0
η, deg	1.30	1.65	2.95	6.05	12.35	.75	1.95	5.15	11.35	-3.7	-.4	3.2	7.0	1.30	2.95	6.05	12.35	-3.7	-.4	3.2	7.0
C_{Y_β} (Tail off)	-.281	-.282	-.286	-.286	-.401	-.330	-.319	-.305	-.421	-.235	-.235	-.256	-.269	-.281	-.286	-.286	-.401	-.235	-.235	-.256	-.269
C_{l_β}	-.054	-.054	-.057	-.045	-.024	-.051	-.055	-.044	-.024	-.085	-.122	-.149	-.166	-.054	-.057	-.045	-.024	-.085	-.122	-.149	-.166
C_{n_β}	-.064	-.063	-.062	-.062	-.086	-.042	-.047	-.052	-.076	-.066	-.066	-.066	-.066	-.064	-.062	-.062	-.086	-.066	-.066	-.066	-.066
C_{Y_p}	.138	.148	.196	.312	.427	.155	.210	.314	.425	.078	.194	.310	.426	.138	.196	.312	.427	-.078	.194	.310	.426
C_{l_p}	-.283	-.283	-.284	-.286	-.288	-.332	-.317	-.305	-.302	-.284	-.286	-.288	-.297	-.283	-.284	-.286	-.288	-.284	-.286	-.288	-.297
C_{n_p}	-.012	-.013	-.020	-.034	-.045	-.011	-.018	-.032	-.043	-.020	-.034	-.050	-.060	-.012	-.020	-.034	-.045	-.020	-.034	-.050	-.060
C_{Y_r}	-.023	-.025	-.040	-.090	-.160	-.023	-.040	-.090	-.160	-.040	-.090	-.160	-.250	-.023	-.040	-.090	-.160	-.040	-.090	-.160	-.250
C_{l_r}	.085	.090	.113	.170	.227	.106	.131	.185	.241	.171	.232	.292	.356	.085	.113	.170	.227	.171	.232	.292	.356
C_{n_r}	-.008	-.010	-.016	-.040	-.106	-.008	-.016	-.040	-.106	-.032	-.043	-.053	-.060	-.008	-.016	-.040	-.106	-.032	-.043	-.053	-.060
C_{Y_β} (Tail on)	-.668	-.673	-.681	-.681	-.822	-.787	-.774	-.730	-.866	-.640	-.640	-.661	-.674	-.919	-.938	-.938	-1.096	-.903	-.903	-.924	-.937
C_{l_β}	-.102	-.102	-.102	-.082	-.046	-.110	-.110	-.087	-.051	-.147	-.175	-.192	-.199	-.145	-.143	-.117	-.073	-.199	-.221	-.232	-.232
C_{n_β}	.081	.081	.086	.086	.072	.129	.123	.107	.091	.086	.086	.086	.086	.180	.188	.188	.180	.190	.190	.190	.190
C_{Y_p}	.041	.052	.105	.238	.382	.037	.100	.229	.377	-.045	.089	.223	.360	-.043	.024	.167	.330	-.149	-.004	.144	.294
C_{l_p}	-.295	-.295	-.294	-.293	-.290	-.347	-.330	-.313	-.305	-.303	-.300	-.297	-.302	-.309	-.307	-.302	-.295	-.323	-.315	-.309	-.310
C_{n_p}	.024	.022	.014	-.008	-.028	.034	.023	-.001	-.029	.026	.006	-.018	-.035	.057	.047	.022	-.007	.067	.042	.013	-.011
C_{Y_r}	.266	.267	.256	.206	.156	.266	.256	.206	.156	.264	.214	.144	.054	.466	.460	.410	.372	.472	.422	.352	.262
C_{l_r}	.121	.125	.147	.196	.244	.149	.172	.216	.261	.216	.271	.324	.381	.154	.180	.226	.265	.258	.308	.355	.405
C_{n_r}	-.117	-.118	-.127	-.151	-.224	-.136	-.143	-.159	-.231	-.146	-.157	-.167	-.174	-.195	-.207	-.231	-.310	-.228	-.239	-.249	-.256
l	12.1					12.1				12.1				12.35				12.35			
z	4.54					4.54				4.54				5.14				5.14			
ϵ, deg	1.15					1.15				2.0				1.15				2.0			
γ	0					0				0				0				0			
k_{X_0}	2.95					2.95				4.47 for $\frac{W}{S}$ = 33.3; 2.95 for $\frac{W}{S}$ = 79.4				2.95				4.47 for $\frac{W}{S}$ = 33.3; 2.95 for $\frac{W}{S}$ = 79.4			
k_{Z_0}	7.69					7.69				9.81 for $\frac{W}{S}$ = 33.3; 7.69 for $\frac{W}{S}$ = 79.4				7.69				9.81 for $\frac{W}{S}$ = 33.3; 7.69 for $\frac{W}{S}$ = 79.4			

$W/S = 79.4$, $S = 259.5$, $W = 20{,}600$#

[redacted]

$I_z = \frac{W}{g} k_z^2 = \frac{20600}{32.2}(7.69)^2 = \frac{59.1}{32.2}\, 20600 = 37{,}8.0$ [illegible]

[redacted]

TABLE II.— CALCULATED PERIOD AND DAMPING CHARACTERISTICS OF THE

BELL X-2 HIGH-SPEED RESEARCH AIRPLANE

Configuration	C_L	C_{n_β}	C_{l_β}	W/S	h	δ_n (deg)	δ_s (deg)	Lateral oscillation P	Lateral oscillation $T_{1/2}$	Lateral oscillation T_2	Spiral mode $T_{1/2}$	Spiral mode T_2	Damping-in-roll-mode $T_{1/2}$
Flaps and gear up (compressibility effects neglected)	0.3	0.081	-0.102	79.4	0	0	0	2.79	2.75	------	116	-----	0.17
	.4	.086	-.102	↓	↓	↓	↓	2.97	2.36	------	873	-----	.21
↓	.6	.086	-.082	↓	↓	↓	↓	3.42	2.08	------	------	52.3	.26
	.8	.072	-.046	↓	↓	↓	↓	4.28	1.47	------	------	24.5	.31
Flaps and gear up (compressibility effects neglected)	.3	.081	-.102	79.4	35,000	0	0	2.75	3.84	------	209	-----	.33
	.4	.086	-.102	↓	↓	↓	↓	2.88	3.08	------	1571	-----	.40
↓	.6	.086	-.082	↓	↓	↓	↓	3.24	2.70	------	------	91.3	.51
	.8	.072	-.046	↓	↓	↓	↓	3.81	1.83	------	------	43.1	.68
Flaps and gear up (compressibility effects included)	.3	.129	-.110	79.4	35,000	0	0	2.25	3.98	------	------	192	.269
	.4	.123	-.110	↓	↓	↓	↓	2.56	3.62	------	------	125	.335
↓	.6	.107	-.087	↓	↓	↓	↓	3.05	2.91	------	------	55.8	.461
	.8	.091	-.051	↓	↓	↓	↓	3.52	1.89	------	------	33.4	.627
Flaps and gear down (compressibility effects neglected)	.4	.086	-.147	33.3	0	30	55	3.97	------	19.55	63.0	-----	.25
	.6	.086	-.175	↓	↓	↓	↓	4.20	------	63.30	49.7	-----	.30
↓	.8	.086	-.192	↓	↓	↓	↓	4.22	16.73	------	55.4	-----	.35
	1.0	.086	-.199	↓	↓	↓	↓	4.23	6.00	------	138	-----	.40
Flaps and gear down (take-off with full fuel load, compressibility effects neglected)	.4	.086	-.147	79.4	0	30	55	3.27	------	5.43	86.5	-----	.17
	.6	.086	-.175	↓	↓	↓	↓	3.50	------	600	62.7	-----	.22
	.8	.086	-.192	↓	↓	↓	↓	3.45	4.44	------	68.3	-----	.27
	1.0	.086	-.199	↓	↓	↓	↓	3.41	2.06	------	165	-----	.33
Flaps and gear down (modified vertical tail, compressibility effects neglected)	.4	.190	-.199	33.3	0	30	55	2.92	6.33	------	------	97.9	.24
	.6	.190	-.221	↓	↓	↓	↓	3.22	5.51	------	------	61.7	.30
	.8	.190	-.232	↓	↓	↓	↓	3.36	4.07	------	------	38.6	.35
	1.0	.190	-.232	↓	↓	↓	↓	3.42	2.96	------	------	22.5	.40
Flaps and gear down (modified vertical tail, compressibility effects neglected	.4	.190	-.199	79.4	0	30	55	2.36	222	------	------	136	.17
	.6	.190	-.221	↓	↓	↓	↓	2.63	5.02	------	------	83.1	.22
	.8	.190	-.232	↓	↓	↓	↓	2.68	2.33	------	------	50.1	.27
	1.0	.190	-.232	↓	↓	↓	↓	2.68	1.49	------	------	28.9	.33
Flaps and gear up (modified vertical tail, compressibility effects neglected	.3	.180	-.145	79.4	35,000	0	0	1.89	2.24	------	1713	-----	.33
	.4	.188	-.143	↓	↓	↓	↓	2.02	2.07	------	------	215	.40
	.6	.188	-.117	↓	↓	↓	↓	2.30	2.03	------	------	53.0	.51
	.8	.180	-.073	↓	↓	↓	↓	2.49	1.52	------	------	28.7	.68

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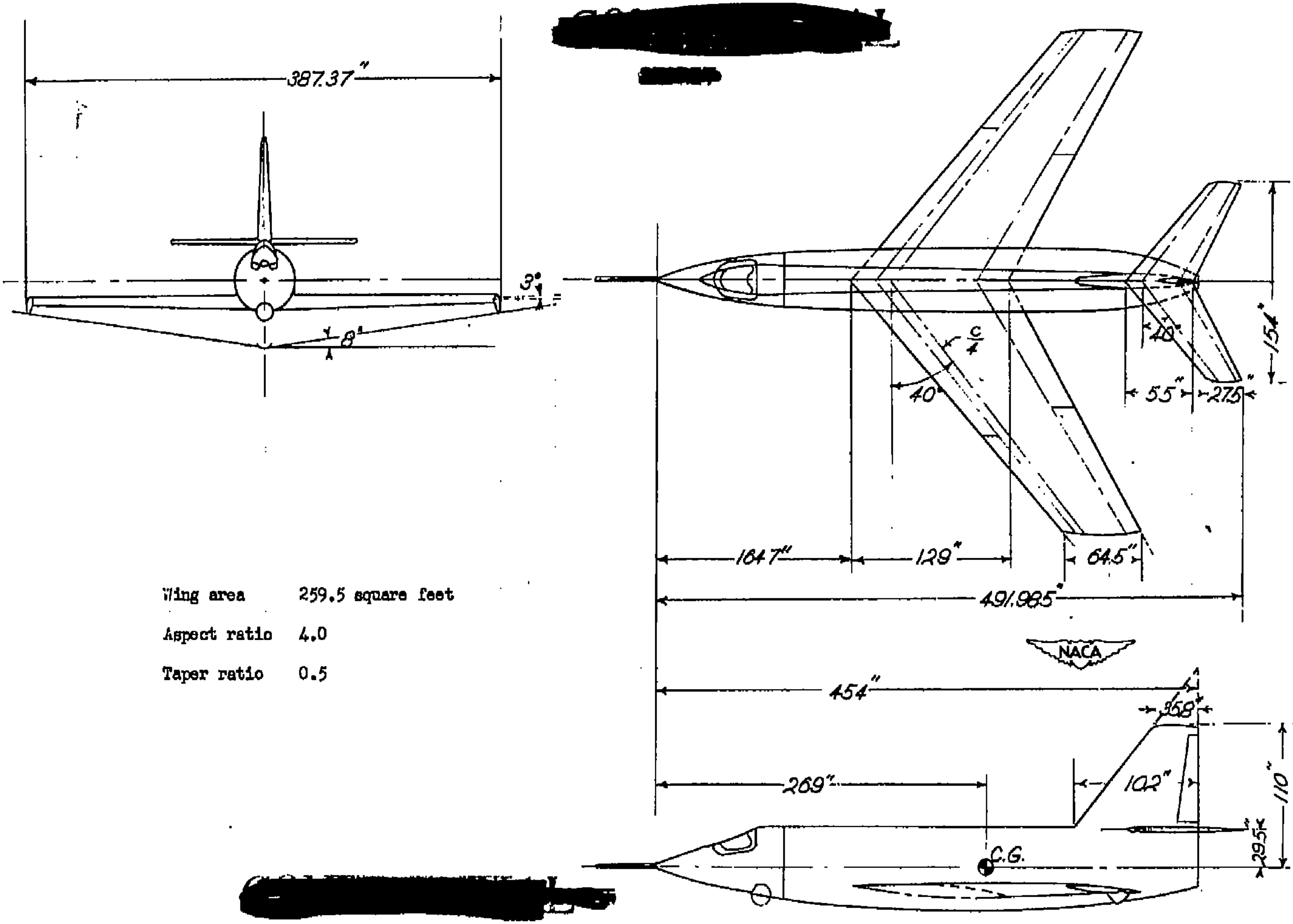

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Figure 1.– Bell X-2 high-speed research airplane.

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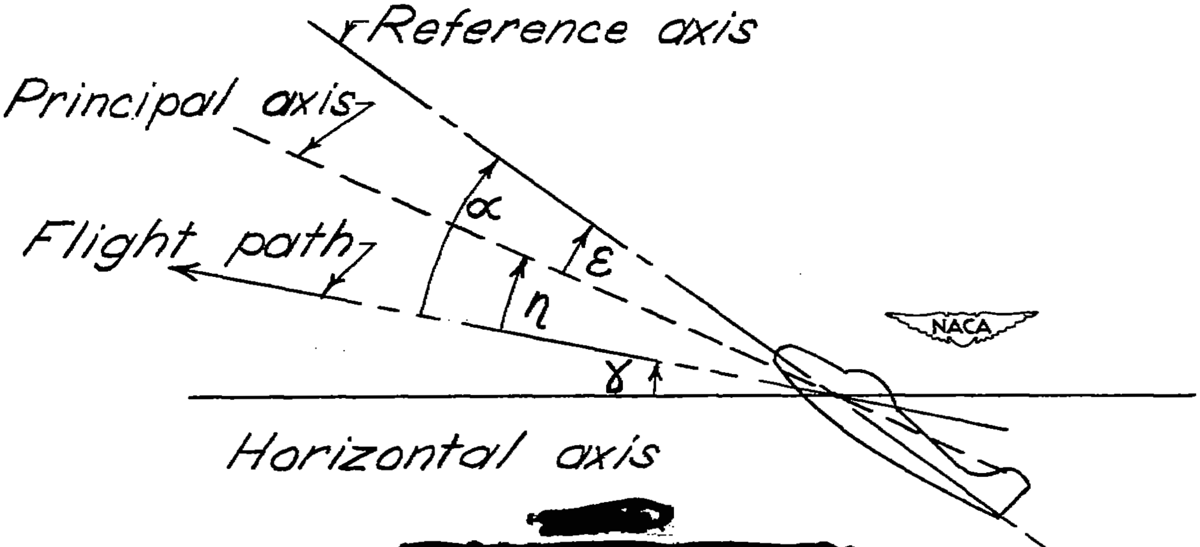

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Figure 2.— Angular relationships in flight. Arrows indicate positive direction of angles.

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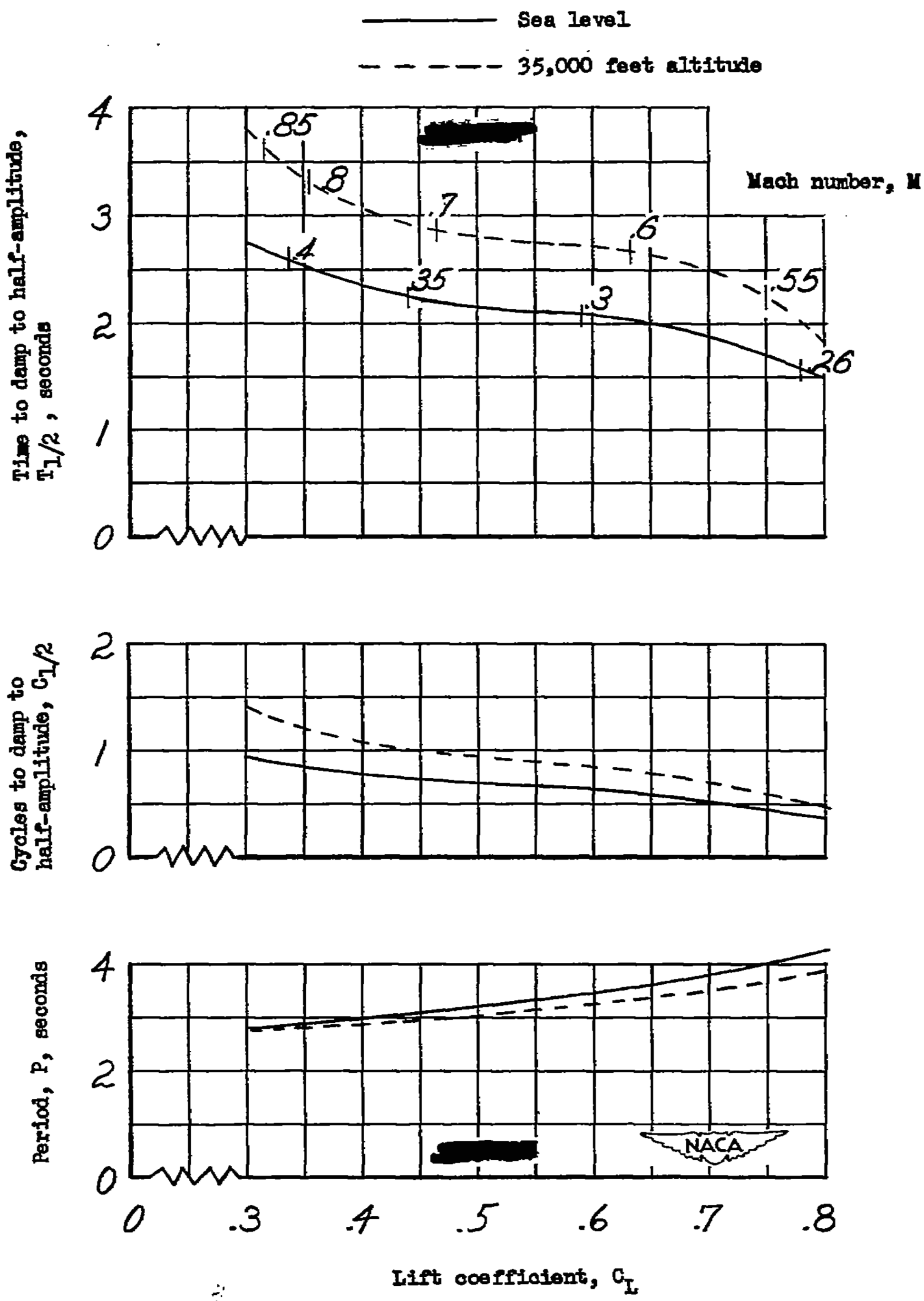

Figure 3.— Calculated effects of altitude on the period and damping characteristics. Flaps and gear retracted. $\frac{W}{S} = 79.4$.

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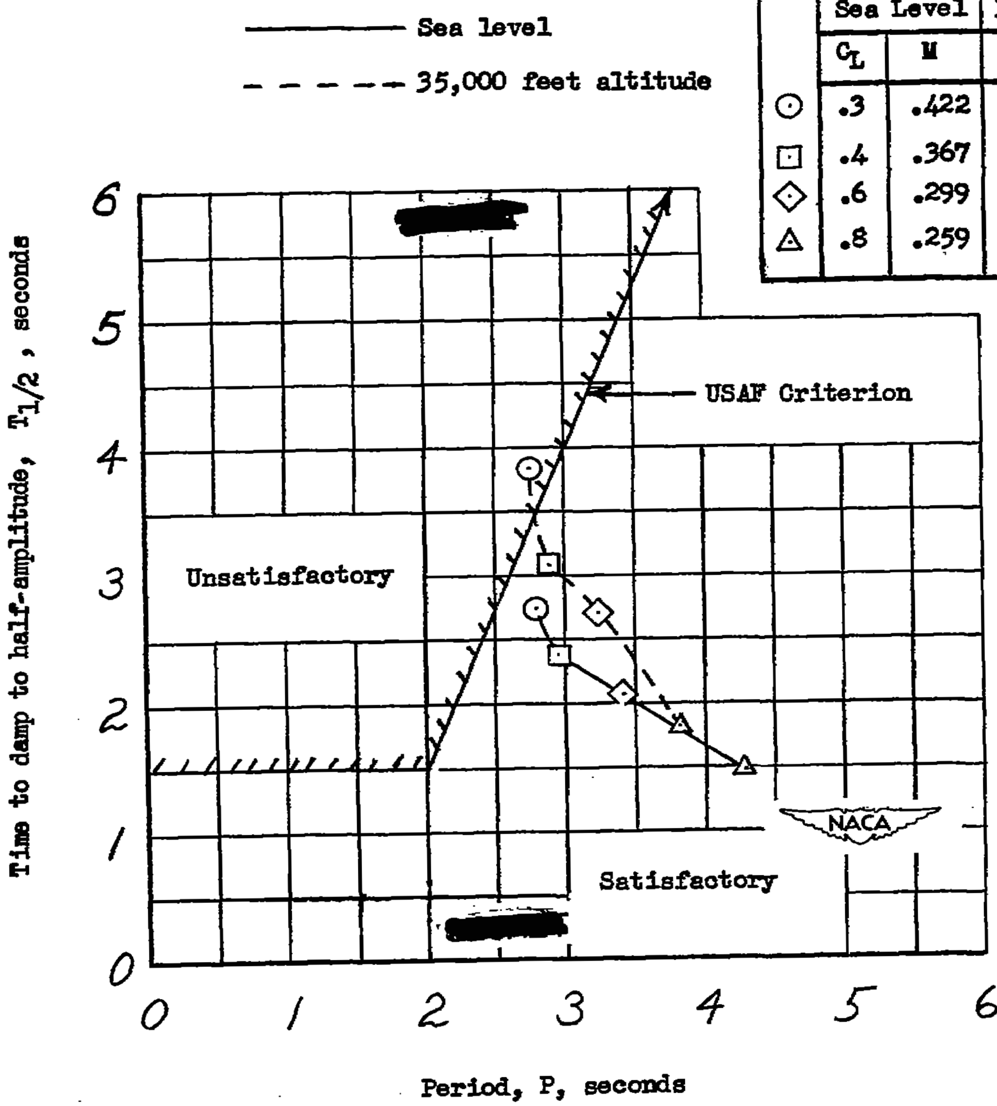

	Sea Level		35,000 Feet	
	C_L	M	C_L	M
⊙	.3	.422	.3	.872
⊡	.4	.367	.4	.755
◇	.6	.299	.6	.617
△	.8	.259	.8	.535

Figure 4.– Comparison of the calculated period and damping of the lateral oscillation with USAF requirement. Flaps and gear retracted. $\frac{W}{S} = 79.4$.

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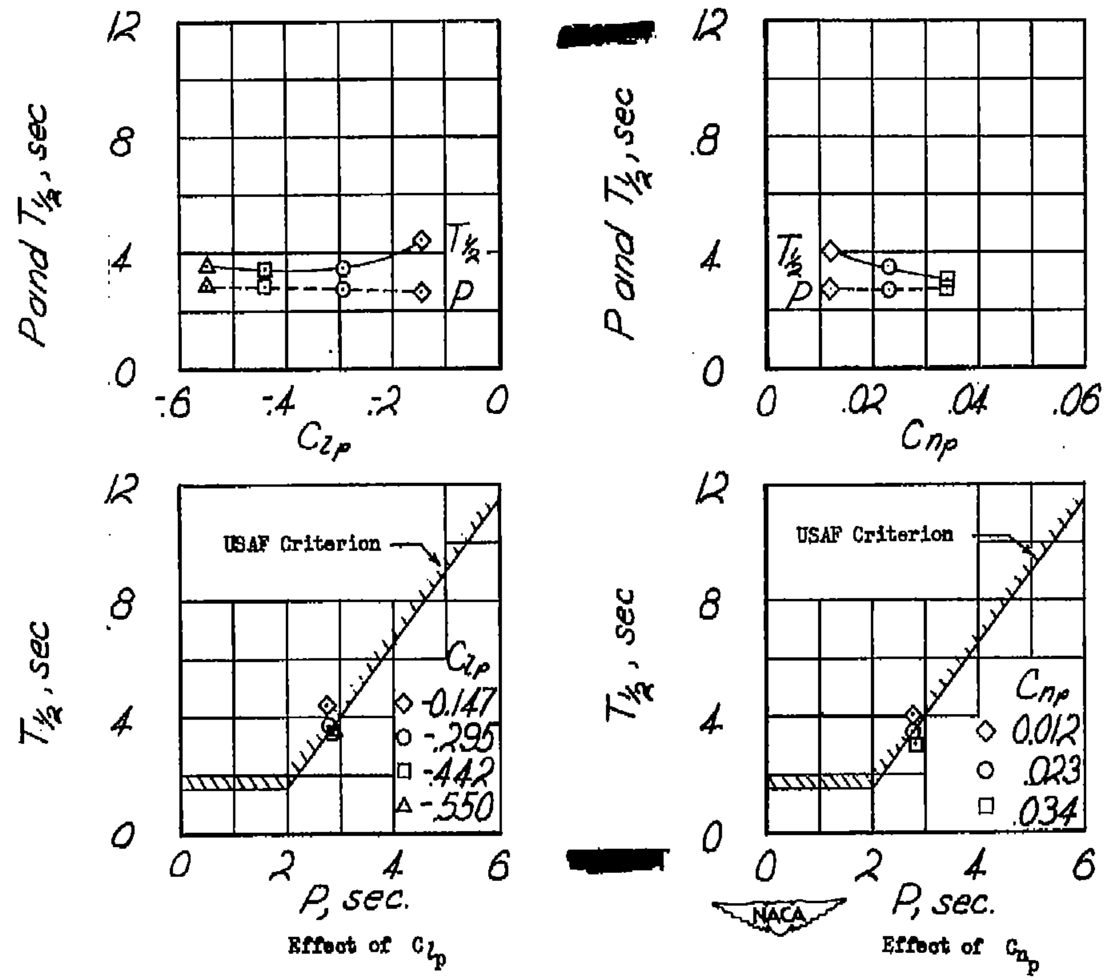

Figure 5.– Effects of variations of C_{l_p}, C_{n_p}, C_{n_r}, k_{X_0}, k_{Z_0}, and η on the period and damping, and a comparison with the USAF criterion. Flaps and gear retracted. $\frac{W}{S} = 79.4$; h = 35,000 feet; M = 0.85; $C_L = 0.316$.

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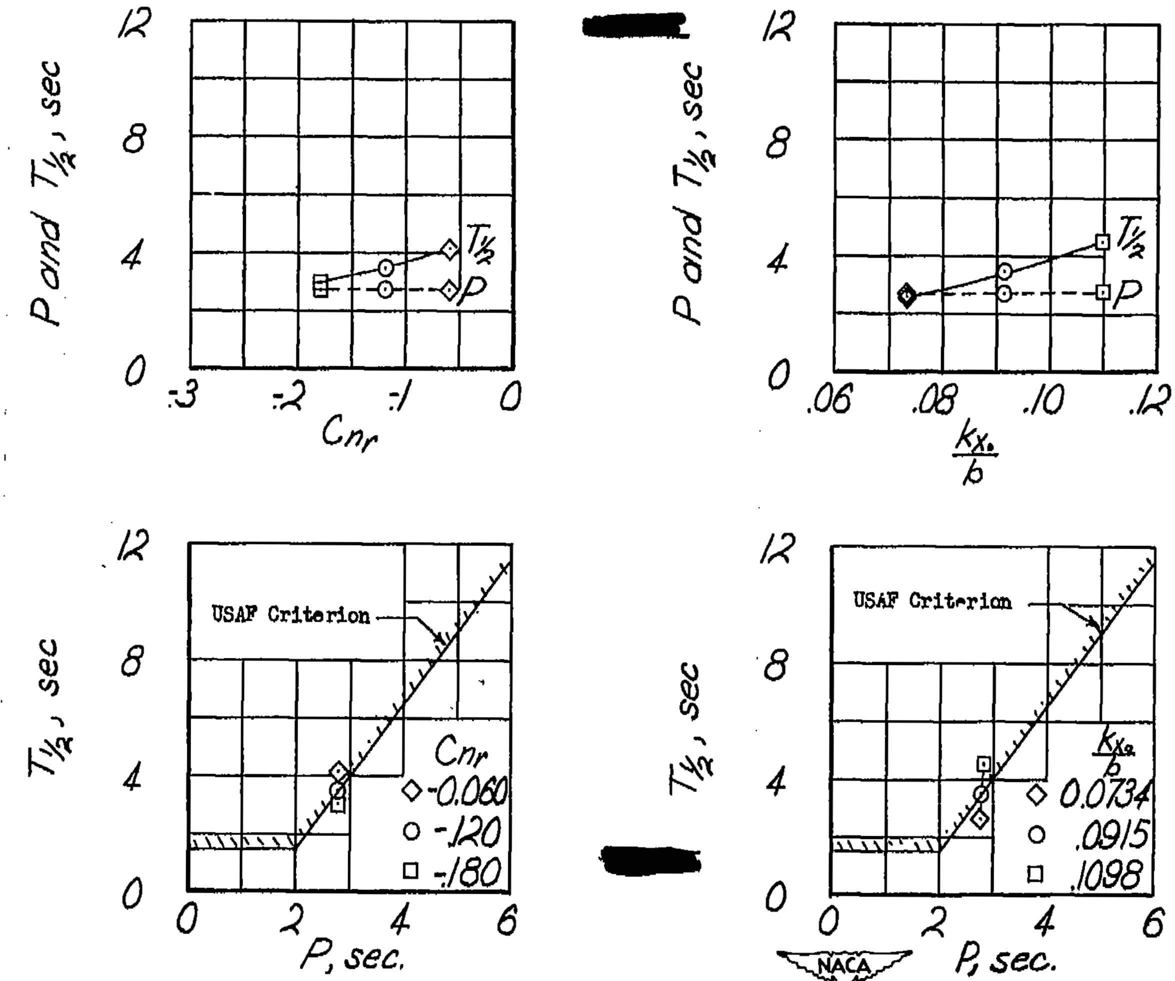

Effect of C_{n_r}

Effect of $\frac{k_{x_0}}{b}$

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Figure 5.– Continued.

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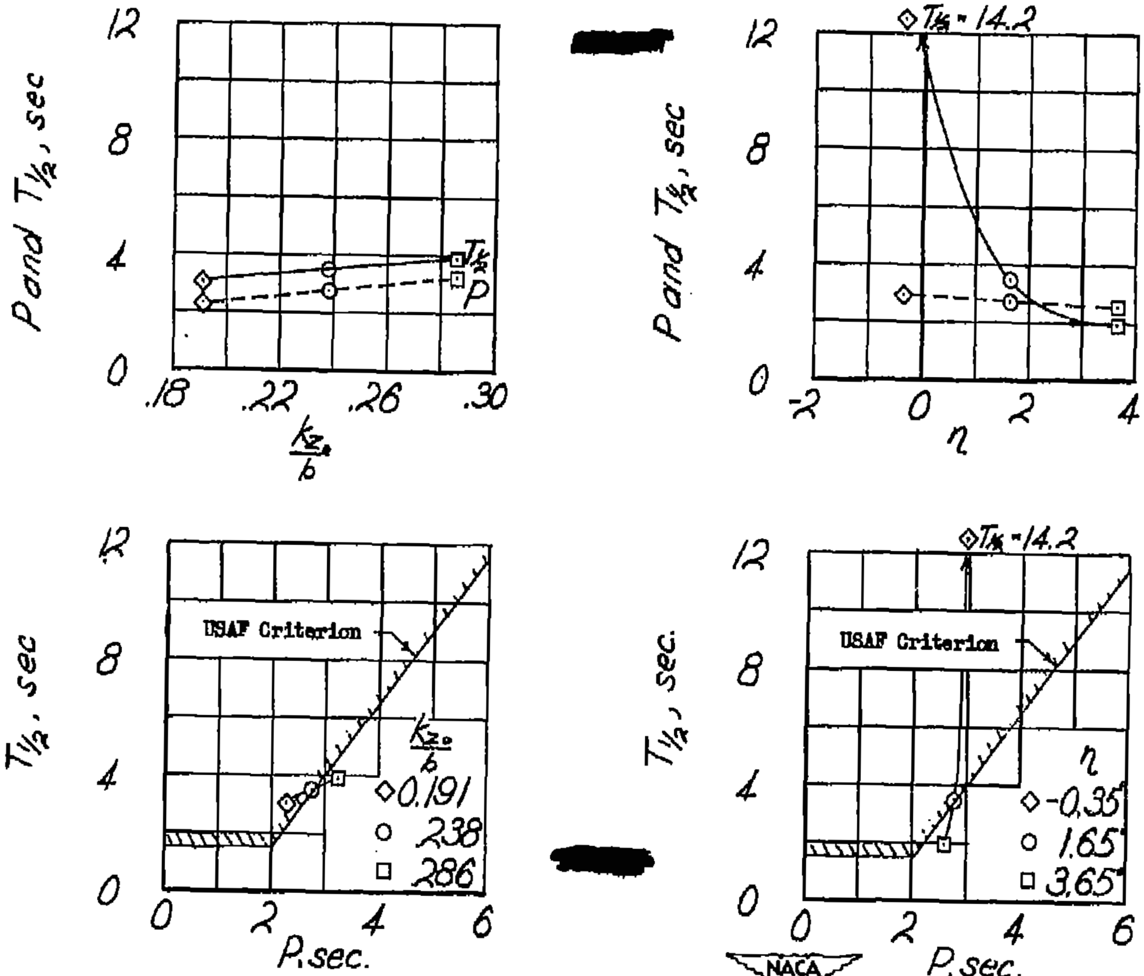

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Effect of $\frac{k_{z_0}}{b}$

Effect of η

Figure 5.— Concluded.

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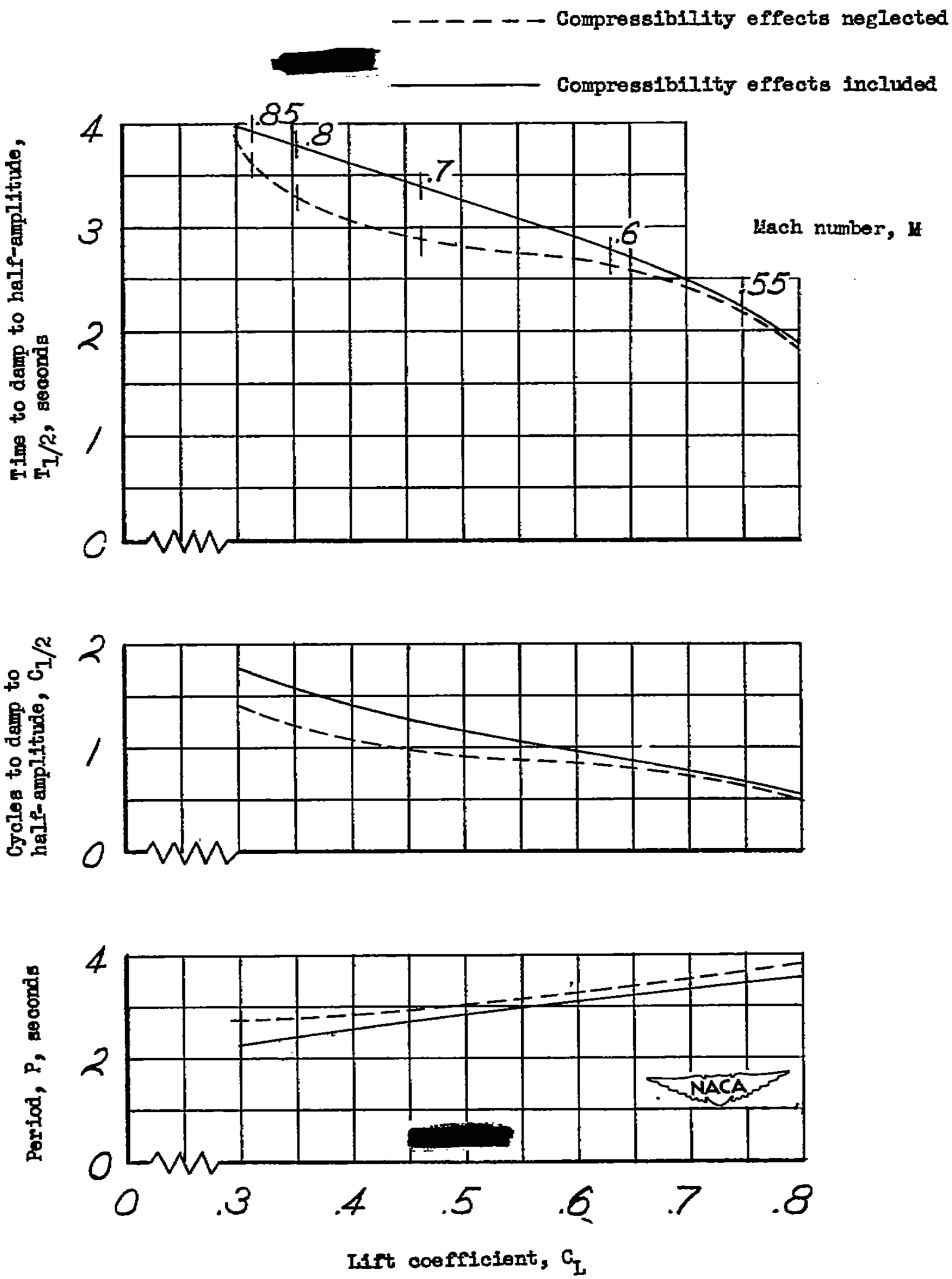

Figure 6.– Calculated effects of compressibility on the period and damping characteristics. Flaps and gear retracted; $\frac{W}{S} = 79.4$; h = 35,000 feet.

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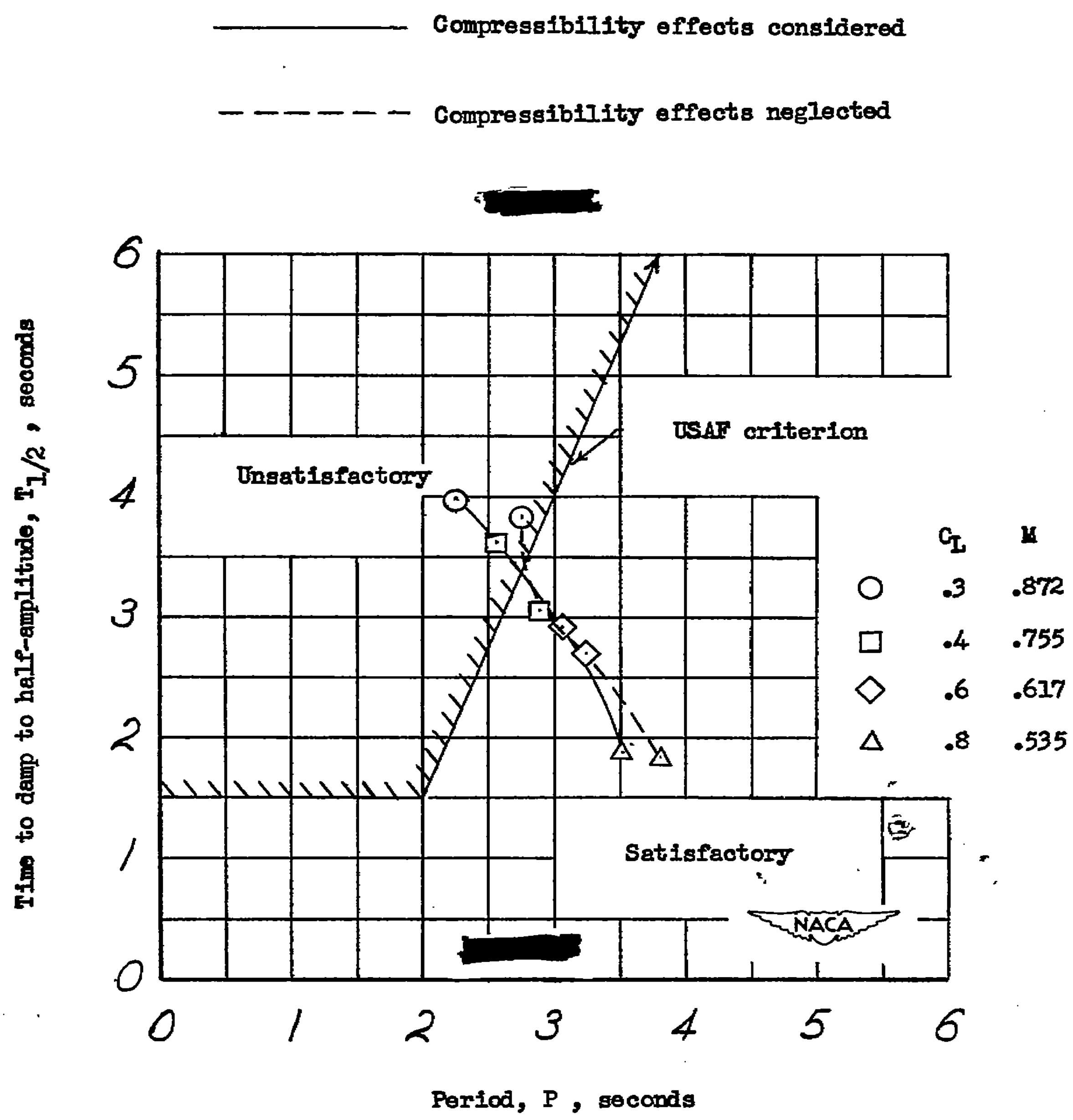

Figure 7.– Comparison of compressibility effects on the period and damping of the lateral oscillation with respect to the USAF requirements. Flaps and gear retracted; $\frac{W}{S} = 79.4$; h = 35,000 feet.

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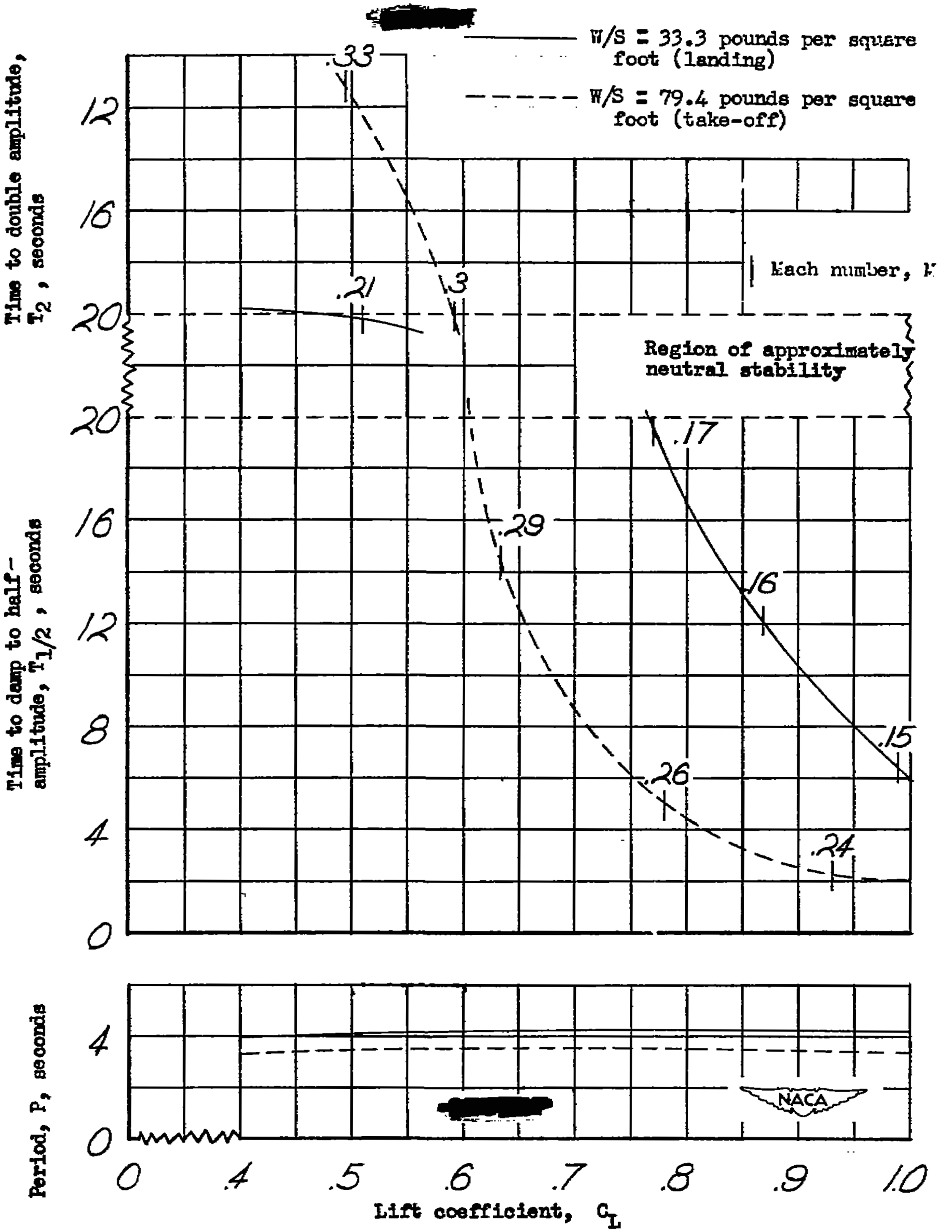

Figure 8.– Calculated period and damping characteristics for sea-level flight. Flaps and gear lowered; $\delta_n = 30^\circ$; $\delta_s = 55^\circ$.

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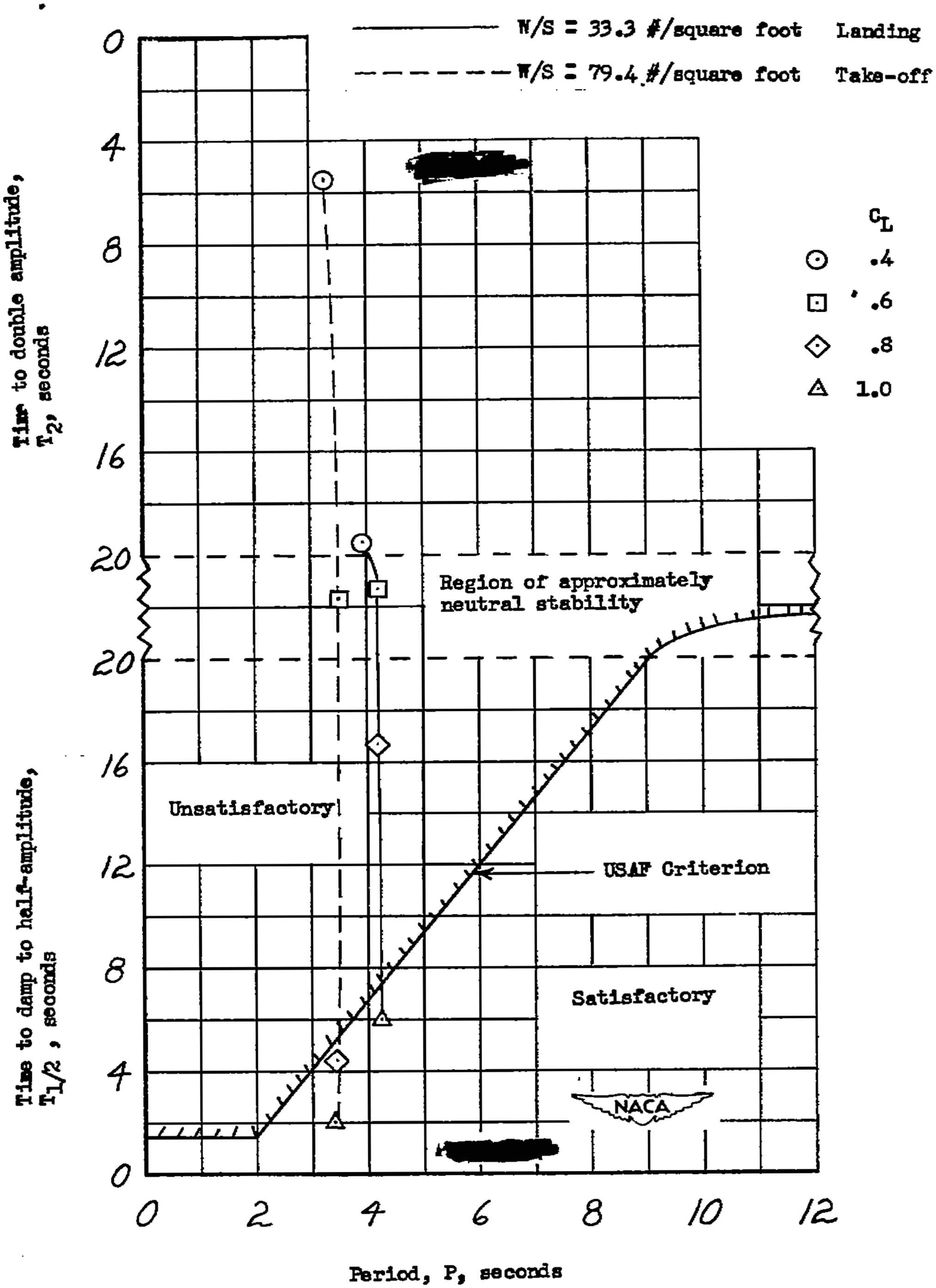

Figure 9.– Comparison of calculated period and damping of the lateral oscillation with USAF requirements. Flaps and gear lowered; $\delta_n = 30^{\circ}$; $\delta_s = 55^{\circ}$; sea-level flight. [redacted]

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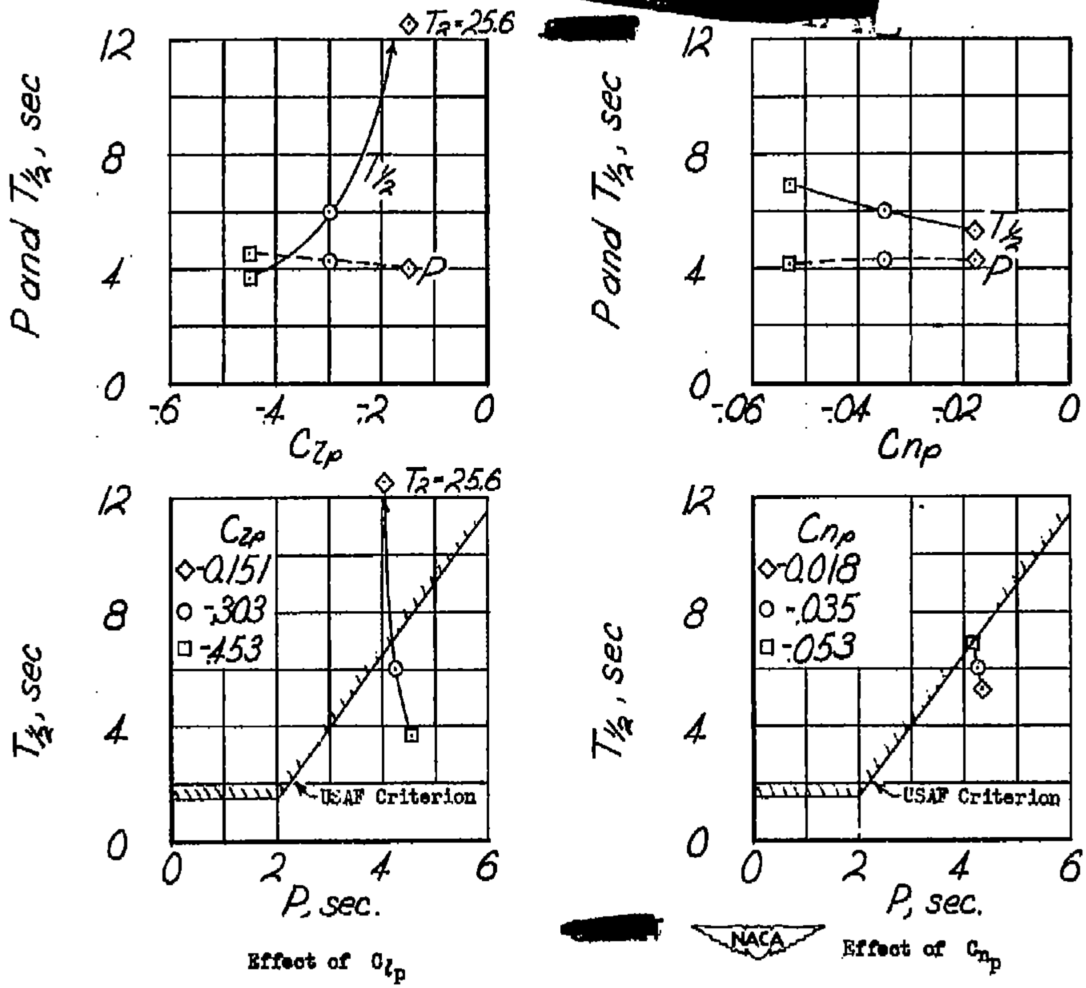

Figure 10.– Effects of variations of C_{l_p}, C_{n_p}, C_{n_r}, k_{X_0}, k_{Z_0}, and η on the period and damping, and a comparison with the USAF criterion. Flaps and gear lowered; $\delta_n = 30^\circ$; $\delta_s = 55^\circ$; $\frac{W}{S} = 33.3$; sea-level flight; $C_L = 1.0$.

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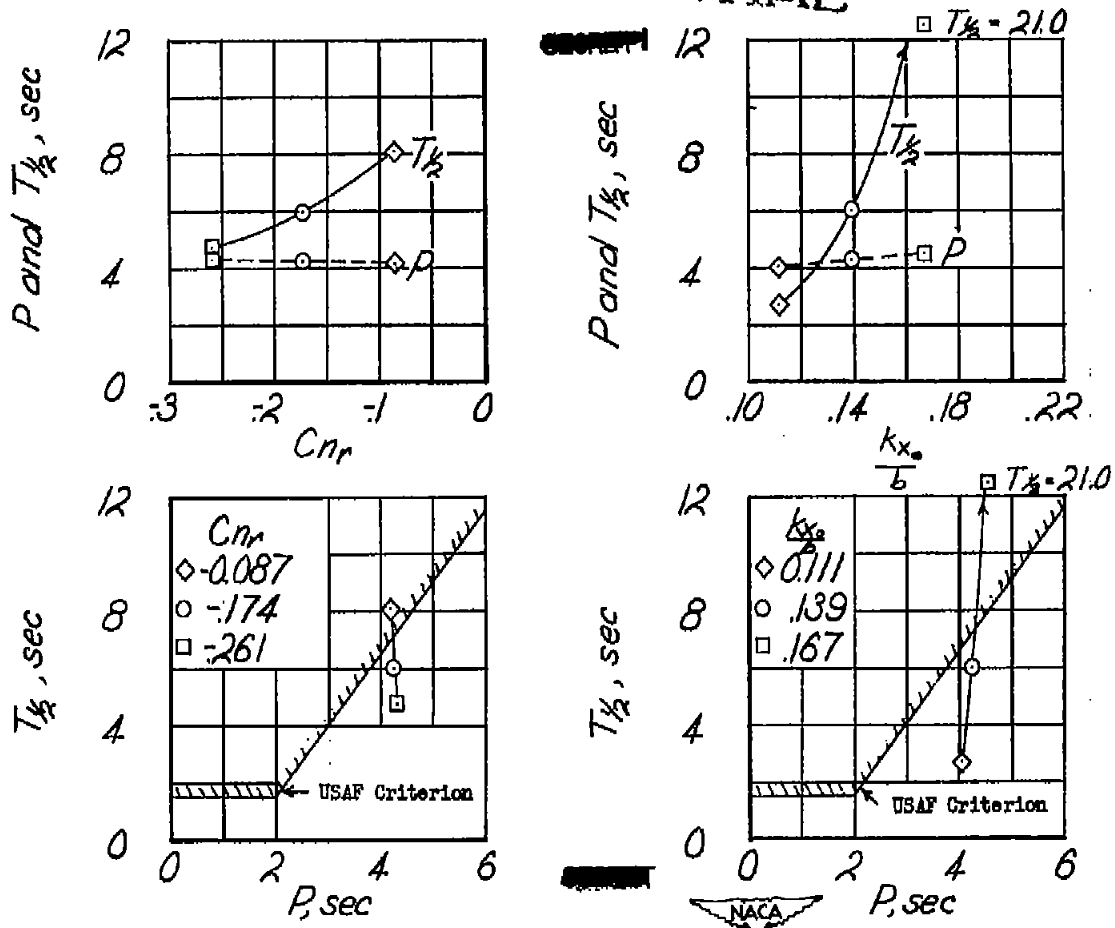

Effect of C_{n_r}

Effect of $\frac{k_{x_0}}{b}$

Figure 10.— Continued.

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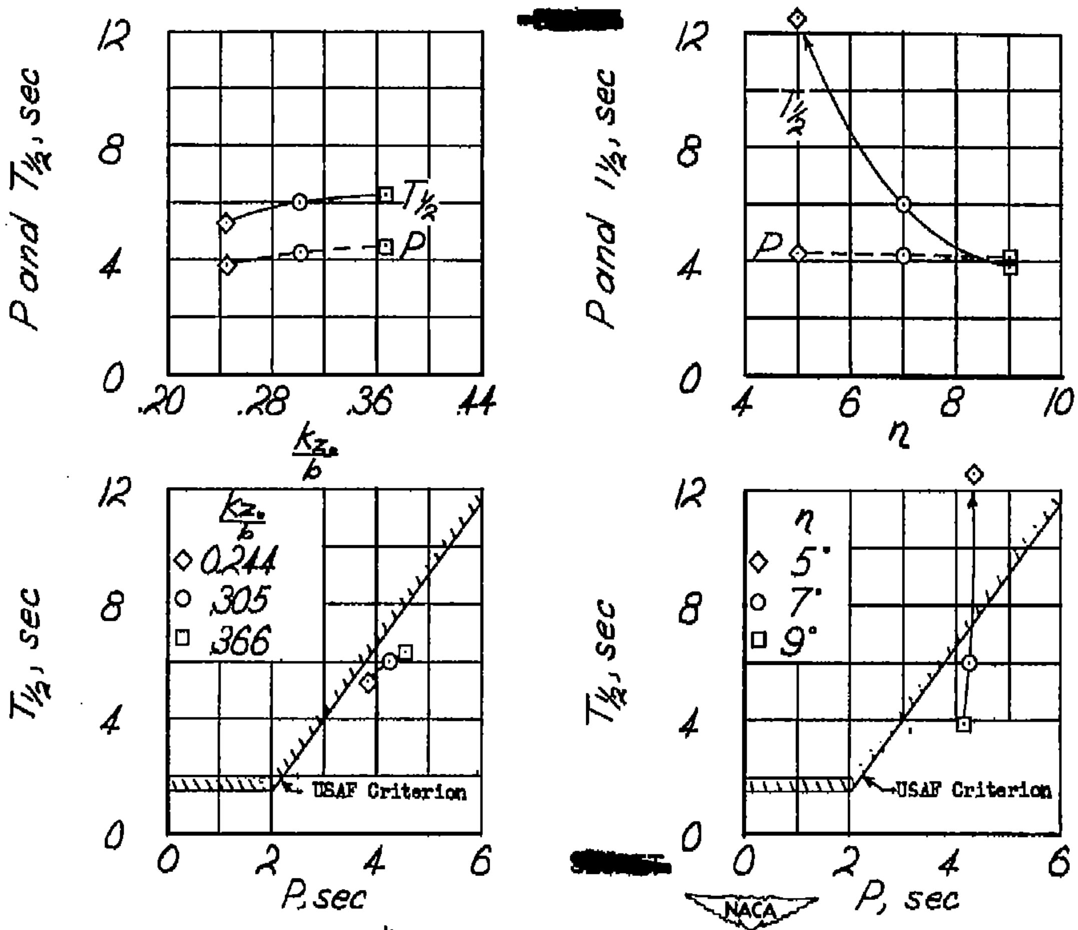

Effect of $\frac{k_{z_0}}{b}$

Effect of η

Figure 10.– Concluded.

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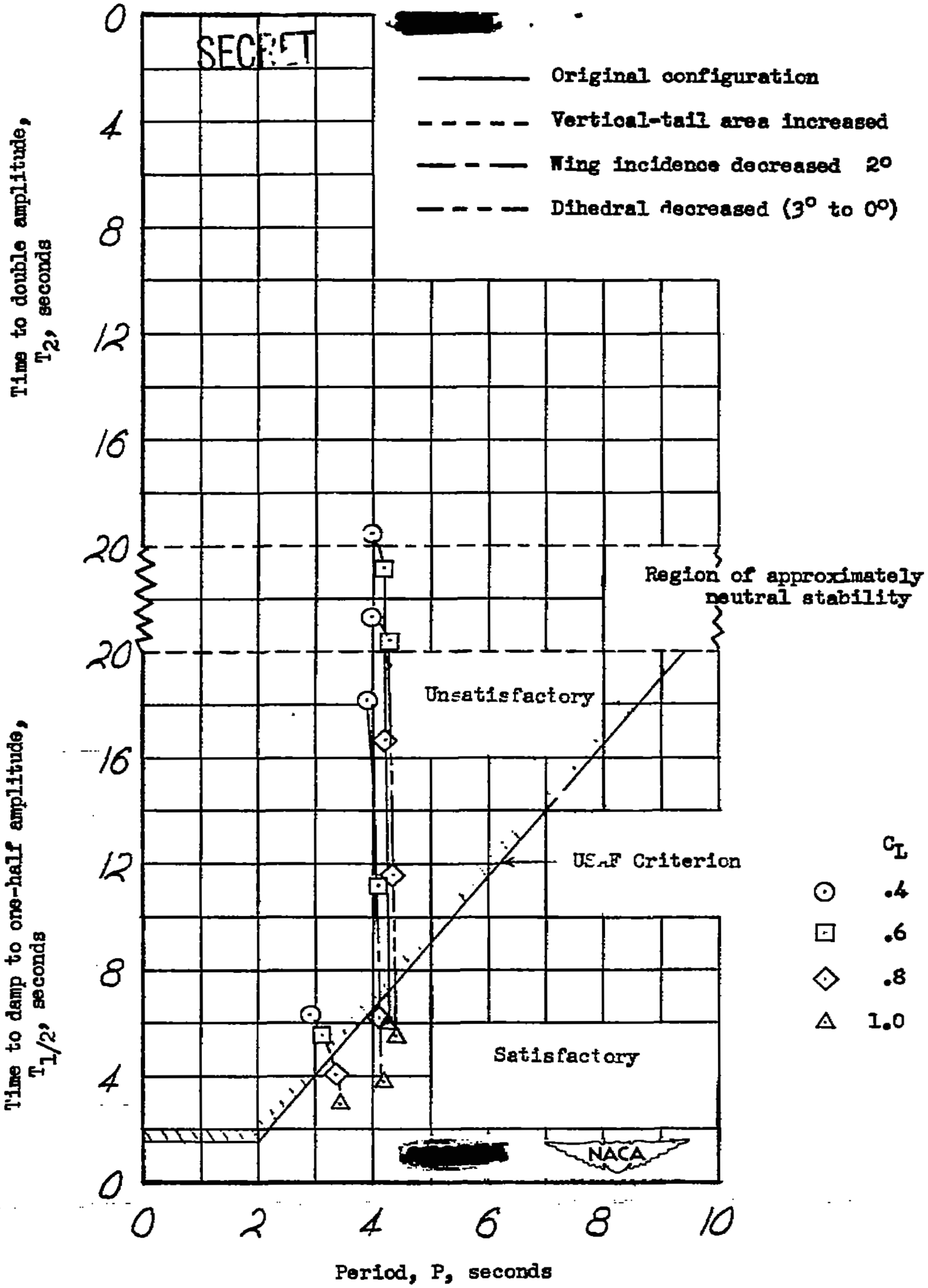

Figure 11.– Effect of assumed modifications on the period and damping results of the airplane, compared with USAF requirements. Flaps down; $\frac{W}{S}$ = 33.3; sea level.

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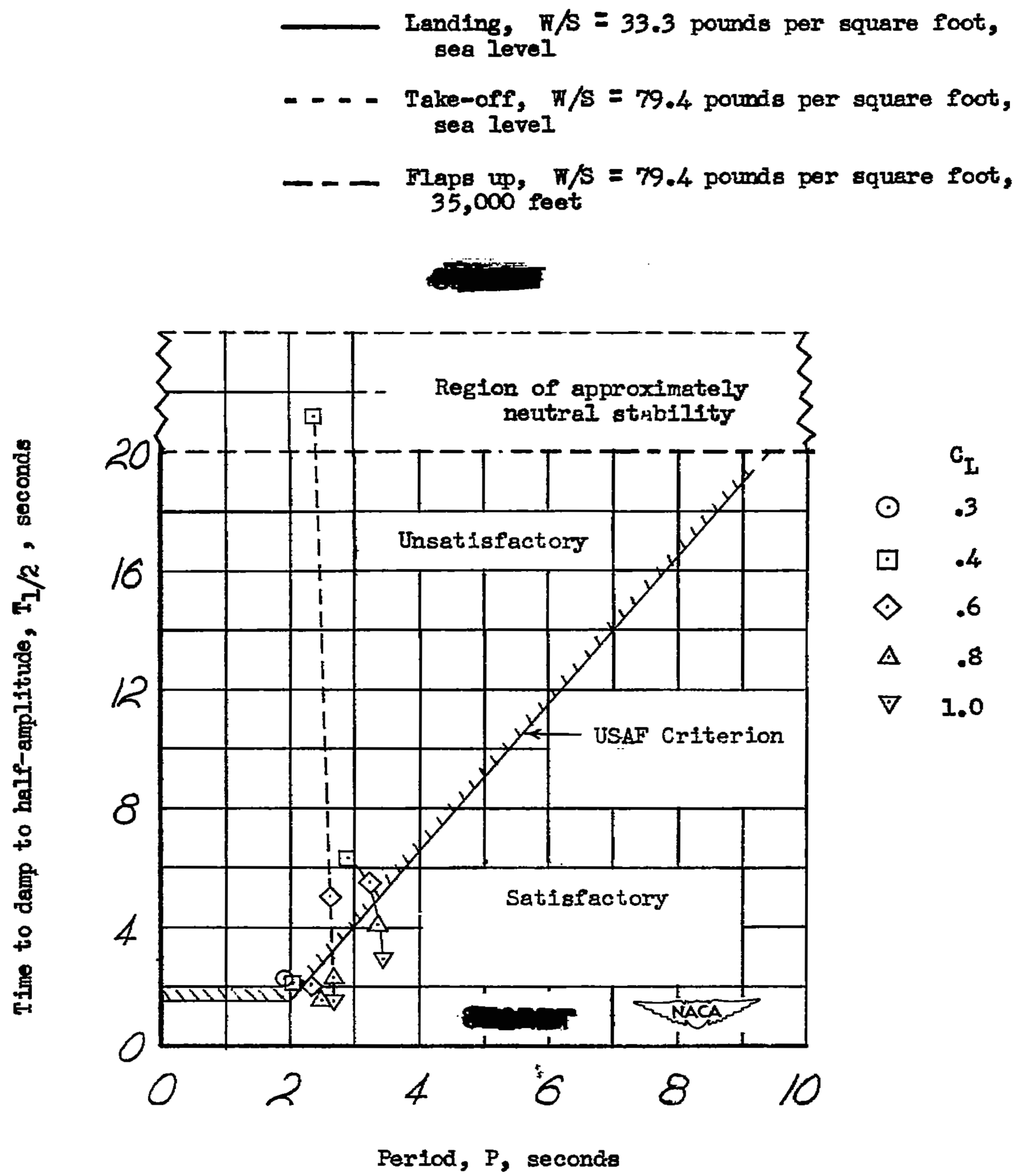

Figure 12.– Period and damping results of the airplane with modified vertical tail, compared with USAF requirements.

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INDEX

ABSTRACT

Contains results of calculations to show the effects of various mass and aerodynamic parameters on the dynamic lateral stability of the Bell X-2 airplane in the landing configuration and in the high-speed configuration at Mach numbers below 0.87. Calculations included determination of the period and rate of damping of the lateral oscillation, and the results are compared with the USAF criterion for satisfactory period-damping relationship.

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